Active target production of muons for muon-catalyzed fusion

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Using a Monte Carlo method, we study the energy efficiency of muon production by a high-energy beam of deuterons, i.e., protons and neutrons, injected into infinite deuterium-tritium targets. We present detailed results for the dependence on target density and beam energy. The key role of secondary (shower) production of muons is demonstrated. Constraints on the possibility of muon catalyzed fusion power reactors are established.

Recent experiments have demonstrated that a single muon can catalyze over 150 deuterium-tritium fusions[1] (and possibly many more), yielding an energy equivalent in excess of 25 muonic masses. This result warrants a serious effort to establish limits concerning the energy cost (in terms of the particle beam energy) for production of negatively charged muons.

Considering the different possibilities particle physics provides for the production of μ^- (direct production of $\mu^+\mu^-$ pairs, excitation of hadronic resonances, e.g., a ϕ meson, in e^+e^- collision, etc.) one is quickly persuaded[2–4] that the only candidate for a technically viable process is the excitation of the delta and other hadronic resonances leading to the emission of pions which then decay into μ^-. Since in N-N collisions at several GeV/nucleon the π^- multiplicity is above one per beam particle, the requirement for 10^{15} π^-/s needed for power generation at MW levels can be accomplished with mA currents, already available at meson factories. In principle, a N-N collision ring could be considered, but, given $\sigma \sim 100$ mb, we would need a luminosity $L_{\rm NN} > 10^{40}/\text{cm}^2\,\text{s}$, which appears unfeasible in conventional schemes (an unconventional one has, however, also been proposed[5]). Similarly, using an e^+e^- ring one would require a luminosity $L > 10^{42}/\text{s}\,\text{cm}^2$, which is far beyond today's technology. (Note that the e^+e^- channel is of similar cost effectiveness as the N-N reactions.)

When a pion is produced in N-N interactions it can itself interact with the target material.[6] A π^- may undergo a charge exchange reaction; the resulting π^0 then decays in $\sim 10^{-16}$ s into 2γ before it interacts. Also, pions can be absorbed on more than one nucleon in a target nucleus, unless when using hydrogen (protium) as the target. However, then the pion production would be weighted to the π^+ channel, and the probability for charge exchange reactions would be enhanced. Clearly, deuterons come as close as possible to being the ideal target; owing to the unusually large average distance between p and n, the pion absorption in flight is about 3 times weaker than that given by extrapolations based on the nucleon number. Still, upon having been stopped, the pionic atom of deuterium will be formed. Then, in an environment with density similar to that of liquid hydrogen (LHD), quenching of high l states to $l=0$ is significant and the observed lifetime resulting from the absorption of the pion in the $(d\pi)$ atom is $\sim 10^{-12}$ s,[7] too little to permit any important muon production after pionic atom formation. Hence, μ^- production is limited to the decay of π^- in flight.

In the conventional approach one then takes a solid target from which pions emerge through the surface into a low-density environment where a pion decay channel is formed with the help of magnetic fields. However, as our Monte Carlo calculations show, most primary pions produced in N-N interactions are lost since the target, if it is designed to stop the beam, absorbs a large fraction of pions as well, and if it is not designed to stop the beam, wastes the beam energy, unless the beam can be successfully reused. Note that it is practically impossible to recirculate deuterium beams since deuterons would be largely (Coulomb) disintegrated in the "thin" target and lost.

For reasons of technological feasibility, and also because in the end, as we shall see, such an arrangement produces muons more energy efficiently, we consider here a deuteron beam dumped into the fusion vessel filled with a D-T mixture and possibly containing auxiliary targets. To anticipate our results, already at a density 0.15 of LHD in the beam area of the active vessel, there are minimal absorption and charge exchange losses with most pions decaying in flight.

In our present study we employ the FLUKA87 Monte Carlo code[8] maintained at Conseil Européen pour la Recherche Nucléaire (CERN) for the purposes of shielding and target design. This program follows all shower particles and utilizes all available experimental data and theoretical particle production models, and interpolations and extrapolations of data. Since the program has not been specifically oriented towards our goal, some minor improvements and corrections had to be made. For example, we have added a realistic treatment of π absorption in deuterium, and we had to consider stopped pions as lost for the purpose of μ production.

The first calculation concerns the energy cost per muon as a function of beam energy using a D-T infinite target and varying the target density. We find that there is very little dependence on the relative D-T proportions. Thus in Fig. 1 we present only the results for the pure tritium target using p and n beams; this reflects on our belief that a d beam will mostly disintegrate upon entering through some window arrangement (capable of containing some hundreds at pressure) into the fusion vessel. Results are shown for $\phi=\rho/\rho_{\mathrm{LHD}}=0.1$, 0.5, 1. The (statistical) error bars shown are the inverse square roots of the total number of negatively charged pions produced in the Monte Carlo sample. Each point is derived from about 250 beam particles and takes $\sim$2 CPU min of IBM3081. Consider first Fig. 1(a), for the neutron beam. We see that at $\phi=0.1$ the energy per muon is very small; it decreases slightly with decreasing beam energy down to the Δ resonance energy. The minimum energy per muon is about 2 GeV, which constitutes a lower limit on the energy cost in our scheme. In Fig. 1(b), we see that for the proton beam at $\phi>0.5$ there is a broad minimum around 3 GeV. For $\phi=0.1$ the cost per muon is about 2.5 GeV. For beam energies larger than 3 GeV both p and n projectiles lead to similar results since then pions are produced dominantly in secondary showers, as we will discuss quantitatively below. We thus conclude that for moderate density, i.e., $0.1 \lesssim \phi \lesssim 0.5$, the optimum energy of the deuteron beam is in the vicinity of 3 GeV/nucleon. This optimum arises since, at lower energies, protons are much less effective in the generation of π^-. Towards the high energies there is a slow increase in energy per pion, based on known particle multiplicities in the showers. Clearly, because of technological considerations, but also because one needs to confine the particle shower in the target, the practical optimum beam energy is at the lowest possible point. Hence, our conclusion.

In the active target the number of fusions per muon will be controlled also by the density of the D-T mixture, since at low densities the muon will decay before having exhausted its fusion potential. Therefore, one would like to provide a lower-density region for allowing the π^- to decay in flight while providing a higher-density region to increase the catalysis cycling rate. Besides considering auxiliary targets in the reaction vessel one may contemplate having a higher temperature in the region of the beam than in the outlying region where the bulk of the fusion reaction would be taking place. In other words, it appears essential to have a dynamical system in which substantial density/temperature gradients are available. The detailed study of such an actual reactor system is, however, beyond our current means or intentions.

Concerning the losses from pion absorption we show in Fig. 2 for the case of a 3 GeV deuterium beam on a tritium target the fraction of pions surviving until stopped and hence being probably lost for the purpose of muon production. Note that up to $\frac{2}{3}$ of π^- is lost at $\phi \gtrsim 1$, their being stopped before decay.

Our methods and results differ from the earlier work of Petrov *et al.*[3] and Eliezer *et al.*[4] in that we have incorporated the particle shower explicitly into our considerations using the Monte Carlo procedure. The significance of this technically difficult step is illustrated in Fig. 3 where we show the ratio of π^- made in the first collision ($n^{(1)}_{\pi^-}$) with respect to all pions made ($\pi^{\mathrm{tot}}_{\pi^-}$) as a function of the deuteron beam energy. While at very low energies (0.5 GeV/nucleon) we see the dominance of the primary pions, this ratio decreases rather rapidly with energy, with almost twice as many secondary π^- than primary ones at $E_{\mathrm{beam}} \sim 3$ GeV/nucleon. This is the reason why our calculation yields negative muons for about half the energy cost given in Ref. 4. In our opinion it will be even more essential to employ the

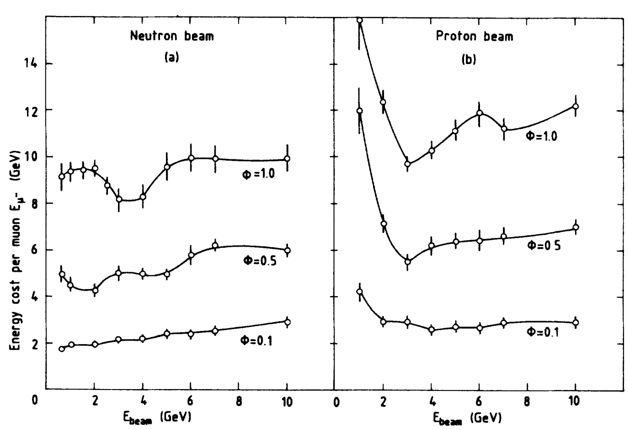

FIG. 1. Energy cost per muon as a function of beam energy for (a) a neutron beam and (b) a proton beam. Results are shown for tritium target and density relative to liquid hydrogen density $\phi=1$, 0.5, 0.1. Error bars show statistical Monte Carlo errors only. Systematic errors due to theoretical extrapolation of scarce cross section data may be more significant.

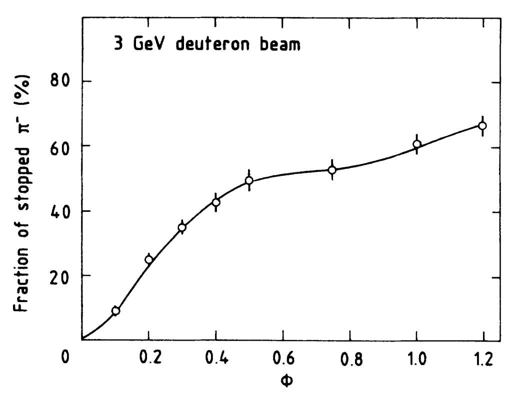

FIG. 2. Fraction of all π^- produced which are stopped as a function of density ϕ of a T target at a 3 GeV/nucleon d beam.

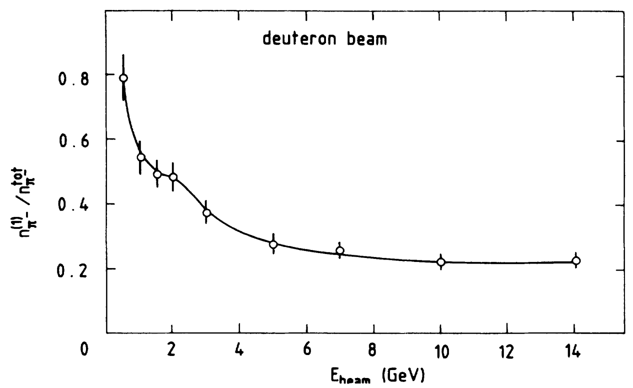

FIG. 3. Fraction of first-interaction π^- of all π^- generated as function of beam energy.

Monte Carlo method when investigating muon production in any realistic finite size reactor vessel with auxiliary targets.

There is a further constraint on muon catalyzed fusion; it arises from the finite lifetime of the tritium. The active target dimensions should be such that the amount of tritium lost by its decay should not exceed a fraction, say 0.6, of tritium burnt in the fusion reaction. In order to estimate the maximum inventory possible we assume here that per each dt fusion 1.6 tritium nuclei will be bred. This is a conservative estimate since each lost π^-, both by absorption and by charge exchange, yields two neutrons and all charged shower particles participate in the Coulomb disintegration of the target deuterons.

Given a desired thermal power P (MW) and an effective fusion yield E_f (MeV) one obtains for the required fusion rate

$$R_f=\frac{P}{E_f}6.24\times10^{18}/\text{s} \ . \tag{1}$$

E_f is not simply the $d+t\rightarrow\alpha+n$ fusion yield, 17.6 MeV, but it also must contain the energy 1.6×4.9 MeV gained in the breeding of tritium, e.g., by neutron absorption in ^{6}Li, and further, the energy brought in by the beam to generate a muon, prorated per fusion. Hence, we find as the effective thermal energy released per fusion:

$$E_f=25\text{ MeV}+E_\mu(\text{MeV})/Y_f \ , \tag{2}$$

where E_μ is the energy cost per muon, and Y_f is the number of fusions per muon. Note that the last term in Eq. (2) must be less than 15% of E_f in order for the fusion scheme to be a viable energy generating system; otherwise too much of the total reactor energy would have to be recirculated into the muon production. Note that at $Y_f\sim500$ and $E_\mu\sim2.5$ GeV the beam heat contributes ~5 MeV out of the total, 30 MeV. Using Eq. (2) for E_f and a design power of $P=3000$ MW (thermal), we find that the rate of fusions required by Eq. (1) is 6.24 10^{20}/s, corresponding to 2×10^{28} tritons/Y (100 Kg/Y), to be compared with the decay loss in one year of 56 kg for a tritium inventory of 1000 kg. At liquid hydrogen density this assumed inventory corresponds to 4.7 m^3 tritium. At $\phi\sim\frac{1}{3}$ and equal D-T mixture, thus, the total active reactor volume may be as large as 28 m^3.

With this geometric constraint on hand, we qualitatively considered a fusion reactor vessel design. We have explored various arrangements and found a strong dependence on the key parameters, such as a magnetic field, which can be used to confine the volume accessible to the produced pions, and also can serve to sweep out the produced π^- into desired areas of the fusion vessel. In simple reactor designs we lost about 50% of the energy, mainly due to high energy beam neutrons escaping the limited reactor volume. But in view of the large number of geometric and design parameters characterizing the target properties of the fusion vessel, we believe that this loss can be significantly reduced. Note that the limited volume of the vessel favors the lowest possible energy of the beam. It should be further noted that fusion neutrons will be thermalized before reaching the walls and hence lithium, used to breed tritium, can be dispersed throughout the volume of the reactor and thus provides excellent protection against material deterioration of the fusion vessel. This is a circumstance very different from the magnetically confined plasma fusion devices which operate at much lower density but at very much higher temperatures.

The present systematic basic study has taught us the values of the essential parameters associated with energy-efficient muon production. We have in particular identified ways by which the energy efficiency of muon production can be improved. A path to an ideal arrangement of targets and active vessels has been laid out in which the loss of pions due to charge exchange and absorption can be minimized, yielding as a probable practical lower limit the value of ~2 GeV/μ^- which we have obtained for a deuterium beam entering into $\phi\lesssim0.1$ infinite D,T target.

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